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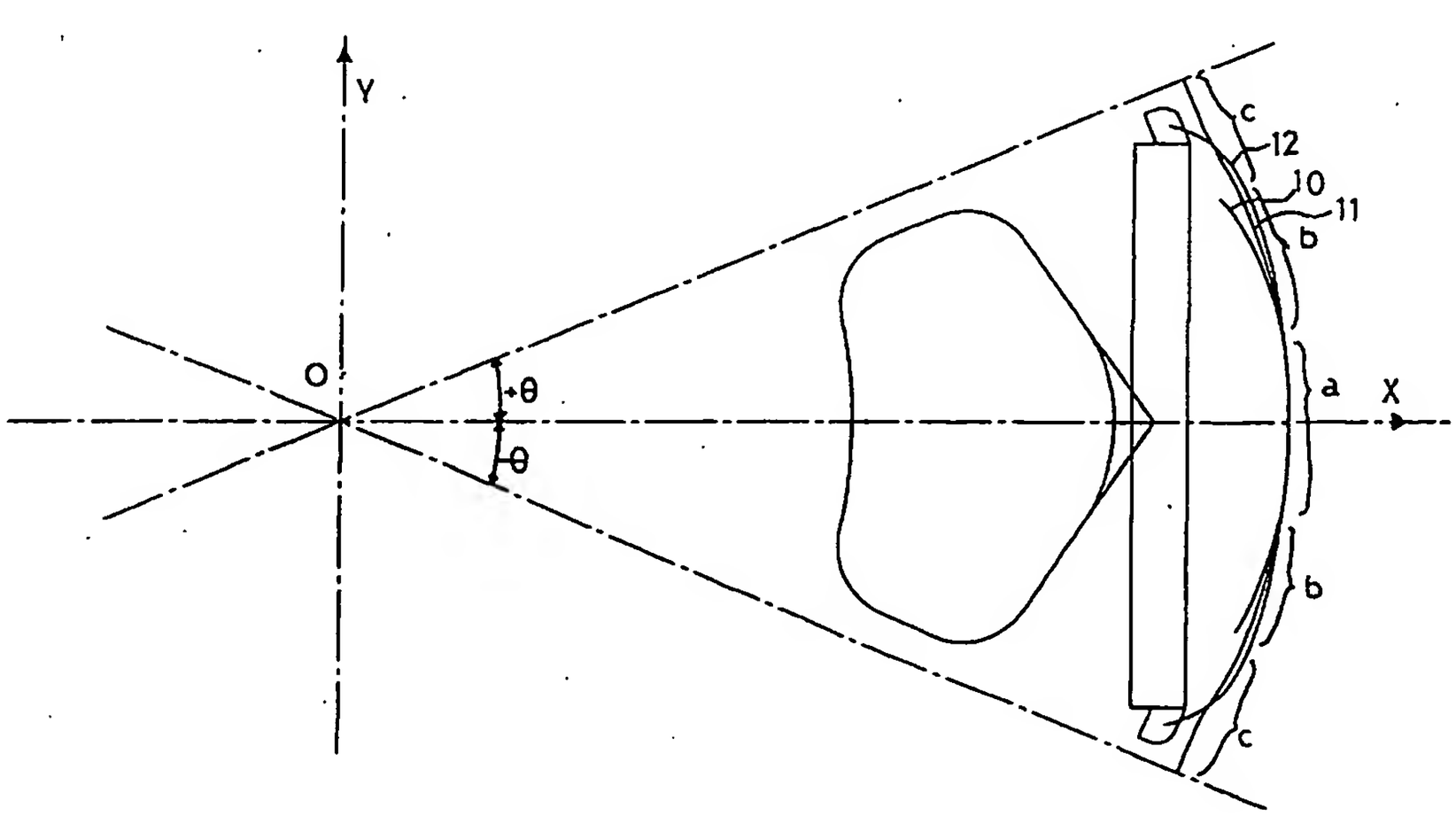
(54) Rotor for synchronous motor

(57) A rotor for a synchronous motor capable of increasing output torque and reducing inductance. An outer periphery of each pole of the rotor in cross section perpendicular to an axis of the rotor is defined on the basis of a curve of a hyperbolic function (10). Since an outer periphery of one pole of the rotor at a central apex portion (a) is substantially identical with that of a conventional rotor defined by a circular arc (11), the output torque of the synchronous motor using this rotor is not decreased. At side portions (b) adjacent to the central apex portion (a), the outer periphery of the rotor pole is positioned inwardly, i.e. closer to the axis (0) of the rotor than the outer periphery defined by the circular arc (11), so that a gap between the outer periphery of the rotor pole and an inner periphery of a stator is made greater at the side portions (b) to reduce the inductance of the synchronous motor.

FIG. 6



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Description

[0001] The present invention relates to a synchronous motor, and in particular to a rotor structure of the synchronous motor.

[0002] In a synchronous motor, torque generation thereof is determined by a gap between an outer periphery of a central portion of each pole of the rotor and an inner periphery of a stator. The torque generation increases as the gap is set smaller. Inductance of the synchronous motor is determined by a gap between an outer periphery of side portions, i.e., regions between the central portion and circumferential ends of each pole of the rotor, and the inner periphery of the stator. The inductance is reduced as the gap is set larger With reduction of the inductance, a counter electromotive force produced in high speed rotation is made smaller,to produce an advantageous effect of increasing output torque (power). Further, the energy efficiency is improved when the inductance is reduced.

[0003] As shown in FIGS. 7 and 8, a conventional rotor of a synchronous motor has an outer periphery of a circle or a shape defined by a combination of circular arcs in a cross section perpendicular to an axis of a rotor. FIG. 7 shows a conventional rotor of a synchronous motor having a circular outer periphery. An outer periphery of each pole of the rotor with magnets 1 embedded therein is defined by a circular arc,and a whole outer periphery of the rotor is defined by connecting circular arcs for the predetermined number of poles to form a circle. A shaft 2 is arranged at a center of the rotor. In this example of FIG. 7, the circular arcs defining respective outer peripheries of the magnets for the predetermined number of poles are arranged on a circle having its center coinciding with a central axis of the rotor (a central axis of the shaft 2) to define the whole outer periphery of the rotor to be the circle.

[0004] In order to increase the output torque of the synchronous motor using the rotor as shown in FIG. 7, it is conceived that a radius of the circle formed by the combination of circular arcs for respective poles is made larger, so as to decrease a gap between a central portion "a" of the rotor and an inner periphery of a stator. However, gaps between the side portions "b" and the inner periphery of the stator are thereby made smaller also, which increases the inductance resulting in decrease of the output torque at high speed rotation. On the other hand, in order to decrease the inductance, it is conceived that the radius of the circular arc is made smaller to increase the gaps at the side portions "b". However, the gap at the central portion is also increased, thereby decreasing the output torque.

[0005] Thus, in order to increase the output torque by reducing a gap between the central portion "a" of each pole and the inner periphery of the stator, it has been proposed to set a center of the circular arc of the outer periphery F of each pole to be offset from the center of the rotor, as shown in FIG. 8. In FIG. 8, magnets 1 are embedded in the core 3 of the rotor and the outer periphery F of each pole of the rotor is defined by a circular arc. A center of the circular arc of each pole is offset from the center of the rotor. The circular arcs for respective poles are connected to define the whole periphery of the rotor. According to this arrangement, the gap between the central apex portion "a" and the inner periphery of the stator is made smaller than the gaps between the outer periphery of the side portions "b" and the inner periphery of the stator. However, with this arrangement, it is not satisfactory to sufficiently increase the output torque and also reduce the inductance of the synchronous motor.

[0006] The present invention improves a relation between torque and inductance of a synchronous motor, and an object thereof is to provide a rotor capable of increasing the torque and reducing the inductance of the synchronous motor.

[0007] A rotor for a synchronous motor of the present invention comprises a plurality of poles and at least part of an outer periphery of one pole of the rotor in a cross section perpendicular to a central axis of the rotor is defined by a curve of a hyperbolic function.

[0008] The most part or the whole part of the outer periphery of the one pole of the rotor may be defined by the curve of the hyperbolic function. Specifically, it is preferable to define a central part of the outer periphery of the one pole by the curve of the hyperbolic function.

[0009] The hyperbolic function may be expressed as $R = A\text{-}B\cdot(e^{C\theta} + e^{-C\theta})$, where R represents a distance from a central axis of the rotor or a fixed point, θ represents a rotational angle from a straight line passing through a center of the outer periphery of one pole and perpendicular to the central axis of the rotor, A, B and C are constants and e is a base of natural logarithm or a constant.

[0010] Alternatively, the hyperbolic function may be expressed as $X = A\text{-}B\ (e^{CY} + e^{-CY})$ on a X-Y coordinate system with a X axis passing through a center of the outer periphery of one pole of the rotor and perpendicular to a central axis of the rotor, a Y axis perpendicular to the X axis and the central axis of the rotor and an origin as a crossing point of the X axis and the Y axis, where A, B and C are constants and e is a base of natural logarithm or a constant.

[0011] In practical machining of the rotor, a region of the outer periphery defined by the curve of the hyperbolic function may be determined based on a train of points on the hyperbolic function curve and a line connecting the train of points by segments of straight lines or curves.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012]

FIG. 1 is a sectional view of a rotor according to a first embodiment of the present invention;

FIG. 2 is a sectional view of a rotor according to a second embodiment of the present invention;
FIG. 3 is a sectional view of a rotor according to a third embodiment of the present invention;
FIG. 4 is a sectional view of a rotor according to a fourth embodiment of the present invention;
FIG. 5 is a sectional view of a rotor according to a fourth embodiment of the present invention;
FIG. 6 is a schematic view showing peripheral shapes of one pole of the rotor;
FIG. 7 is a sectional view of a conventional rotor for a synchronous motor having an outer periphery of a circle;
FIG. 8 is a sectional view of a conventional rotor for a synchronous motor having an outer periphery formed by circular arcs with their centers offset from a center of the rotor.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0013] FIG. 1 shows a cross section of a rotor of a synchronous motor on a plane perpendicular to an axis of a rotor shaft 2 according to a first embodiment of the present invention. Magnets 1 are embedded in a rotor core 3 which is fixed to the rotor shaft 2. An outer periphery F of each pole L of the rotor is defined by a curve of a hyperbolic function. Respective outer peripheries F are connected by a predetermined number of poles to form the whole peripheral shape of the rotor in the cross section.

[0014] FIG. 2 shows a cross section of a rotor of a synchronous motor on a plane perpendicular to an axis of a rotor shaft 2 according to a second embodiment. Likewise the first embodiment, magnets 1 are embedded in a rotor core 3 which is fixed to the rotor shaft 2. This embodiment differs form the first embodiment in that only a part, i.e., a central portion (an apex portion "a" and side portions "b") of the outer periphery F of each pole L is defined by a curve of a hyperbolic function and end portions "c" connecting with outer peripheries of adjacent poles are not defined by the curve of the hyperbolic function.

[0015] FIG. 3 shows a cross section of a rotor of a synchronous motor on a plane perpendicular to an axis of a rotor shaft 2 according to a third embodiment. Magnets each having an outer periphery F defined by a curve of a hyperbolic function are fixed on an outer surface of the rotor core 3.

[0016] FIG. 4 shows a cross section of a rotor of a synchronous motor on a plane perpendicular to an axis of a rotor shaft 2 according to a fourth embodiment. In this embodiment, magnets 1 are arranged radially in the rotor core 3. An outer periphery F of each pole L of the rotor is defined by a curve of a hyperbolic function.

[0017] FIG. 5 shows a cross section of a rotor of a synchronous motor on a plane perpendicular to an axis of a rotor shaft 2 according to a fifth embodiment. The rotor of this embodiment is suitable for a reluctance motor. An outer periphery F of each pole of the rotor is defined by a curve of a hyperbolic function and a groove is formed between the outer peripheries of the adjacent poles.

[0018] The shape of the outer periphery of one pole of the rotor in cross section will be described in detail referring to FIG. 6. In FIG. 6, an X axis is defined as a line crossing a central axis of the rotor (the rotor shaft 2) perpendicularly and passing a central point of an outer periphery of one pole, an origin O is defined as a crossing point of the X axis and the central axis of the rotor, and a Y axis is defined as a line passing the origin O and perpendicular to the X axis and the central axis of the rotor.

[0019] A central angle θ between the X axis and a straight line passing the origin O and a circumferential end of the outer periphery of the one pole is set approximately ± 22° to define an angular width of the outer periphery F of the one pole. In FIG. 6, three lines of a curve 10 of a hyperbolic function, a circular arc 11 and a curve 12 of a function (1/cos) are shown.

[0020] A general formula of the hyperbolic function for defining the outer periphery of one pole may be expressed by the following equation (1).

$$R = A\text{-}B \cdot \cosh(C\theta) = A\text{-}B\cdot(e^{C\theta} + e^{-C\theta})/2 \qquad (1)$$

[0021] In the above equation (1), R represents a distance from the origin O, θ represents a rotational angle from the X axis. "A" represents a constant value determined based on a distance between an inner periphery of the stator and the origin O (a radius of the inner periphery of the stator). "B" represents a constant value determined based on a distance (gap) between an apex of one pole of the rotor (a central point of one pole) and the inner periphery of the stator. "C" represents a constant value defining a curvature of the hyperbolic function.

[0022] An output torque and the inductance are analyzed with respect to shapes of the circular arc, the (1/cos) function and the hyperbolic function shown in FIG. 6 on the basis of FEM (finite element method), to obtain the following results.

	Torque	Inductance
Circular arc	112	1.63 (+11%)
1/cos	113	1.81 (+11%)
Hyperbolic function	110	1.47 (+11%)

[0023] As seen from the above analysis results, the torque to be generated by a rotor with outer periphery of the hyperbolic function curve is slightly decreased but not significantly changed when compared with the torque to be generated by a rotor with outer periphery

of the circular arc curve and the torque to be generated by a rotor with outer periphery of the (1/cos) function curve. On the other hand, the inductance of a rotor with outer periphery of the hyperbolic function curve is greatly reduced. This means that the output torque can be increased when the inductance is set to be the same, and that the inductance can be increased when the torque is se to be the same. Further, the output torque can be increased and the inductance can be reduced by using the rotor with outer periphery of the hyperbolic function curve in comparison with the rotor with outer periphery of the circular arc curve.

[0024] As can be seen form FIG. 6, the three curves are substantially the same at the apex portion "a" of the one pole. However, the hyperbolic function curve 10 is positioned inner, i.e. closer to the origin O, than the circular arc 11 at the side portions "b" on both sides of the apex portion "a" to form the larger gaps between the outer periphery of the rotor and the inner periphery of the stator compared with the circular arc 11. Consequently, it is considered that the output torque is substantially unchanged (because there is no substantial difference between the gaps at the central apex portion), and the inductance is greatly reduced.

[0025] Further, it is considered that the inductance of the synchronous motor using the rotor with the outer periphery defied by the (1/cos) function curve 12 is made greater than that when using the rotor with the outer periphery of the circular arc 11 since the (1/cos) function curve 12 is positioned outer than the circular arc 11 at the side portions "b".

[0026] The shape of the outer periphery at the apex portion "a" and the side portions "b" of the one pole of the rotor is a significant factor for the output torque and the inductance. However, since end portions "c" of the outer periphery of one pole of the rotor are not significant for the characteristics of the rotor, the end portions "c" may be formed into an arbitrary shape other than the hyperbolic function curve unless it influences the torque and the inductance. Such arrangements have been adopted in the foregoing second to fifth embodiments.

[0027] As described above, a synchronous motor with high output torque and low inductance can be obtained with a rotor having an outer periphery defined using the hyperbolic function. The constants A, B and C in the foregoing equation (1) can be determined optimally on the basis of experiments. The constant A is determined on the basis of a radius of the inner periphery of the stator as described (A is determined to be a radius of the inner periphery of the stator in the above example) and the constant B is determined on the basis of the gap between the outer periphery of the rotor and the inner periphery of the stator (B is defined to be a half of the gap in the above example). The constant C defines a curvature of the hyperbolic function curve and thus specifies the outer periphery of the apex portion "a" and the side portions "b". The hyperbolic function curve is determined to be positioned substantially identical with the circular arc 11 at the apex portion "a" and positioned inner than the circular arc 11 at the side portions "b". The degree of positioning inside the circular arc 11 is determined by the constant C. The constant C is determined on the basis of experiments or a simulation based on results of a plurality of experiments, to be optimal so that the output torque is increased and the inductance is reduced.

[0028] The curve of the outer periphery of one pole of the rotor may be defined based on the following equation (2) on the X-Y coordinate system as shown in FIG. 6.

$$X = A - B(e^{CY} + e^{-CY}) \qquad (2)$$

[0029] In the equation (2), A, B and C are constants which are different from the value of the A, B and C in the equation (2). "A" is determined based on a radius of the inner circumference of the stator, "B" is determined based on the gap between the apex of one pole of the rotor and the inner periphery of the stator, and "C" is determined so as to optimize the curvature of the hyperbolic function curve, i.e., the shape of the side portions "b" on both sides of the apex portion "a", as in the equation (1).

[0030] In practical machining of the rotor, a region of the outer periphery defined by the curve of the optimum hyperbolic function may be determined based on a train of points on the hyperbolic function curve and a line connecting the train of points by segments of straight lines or curves.

[0031] With adopting the rotor according to the present invention in the synchronous motor, the inductance of the motor is reduced when the output torque of the motor is set to the same and the output torque is increased when the inductance is set to the same, as compared with the synchronous motor using the conventional rotor. Particularly, the reduction of inductance improves controllability of the synchronous motor and saves energy.

Claims

1. A rotor for a synchronous motor comprising a plurality of poles, at least a part of an outer periphery of one pole of the rotor in a cross section perpendicular to a central axis of the rotor being defined by a curve of a hyperbolic function.

2. A rotor for a synchronous motor according to claim 1, wherein the most part of the outer periphery of the one pole of the rotor is defined by the curve of the hyperbolic function.

3. A rotor for a synchronous motor according to claim

1, wherein the whole part of the outer periphery of the one pole of the rotor is defined by the curve of the hyperbolic function.

4. A rotor for a synchronous motor according to claim 1, wherein a central part of the outer periphery of the one pole is defined by the curve of the hyperbolic function.

5. A rotor for a synchronous motor according to any preceding claim, wherein said hyperbolic function is expressed as $R = A\text{-}B \cdot (e^{c\theta} + e^{-c\theta})$, where R represents a distance from a central axis of the rotor or a fixed point, θ represents a rotational angle from a straight line passing through a center of the outer periphery of one pole and perpendicular to the central axis of the rotor, A, B and C are constants and e is a base of natural logarithm or a constant.

6. A rotor for a synchronous motor according to any of claims 1 to 4, wherein said hyperbolic function is expressed as $X = A\text{-}B(e^{CY} + e^{-CY})$ on a X-Y coordinate system with a X axis passing through a center of the outer periphery of one pole of the rotor and perpendicular to a central axis of the rotor, a Y axis perpendicular to the X axis and the central axis of the rotor and an origin as a crossing point of the X axis and the Y axis, where A, B and C are constants and e is a base of natural logarithm or a constant.

7. A rotor for a synchronous motor according to any one of claims 1 through 6, wherein the outer periphery of one pole of the rotor includes a region defined based on a train of points on said curve of the hyperbolic function and a line connecting the train of points by segments of straight lines or curves.

8. A synchronous motor comprising a rotor according to any one of the preceding claims.

FIG. 1

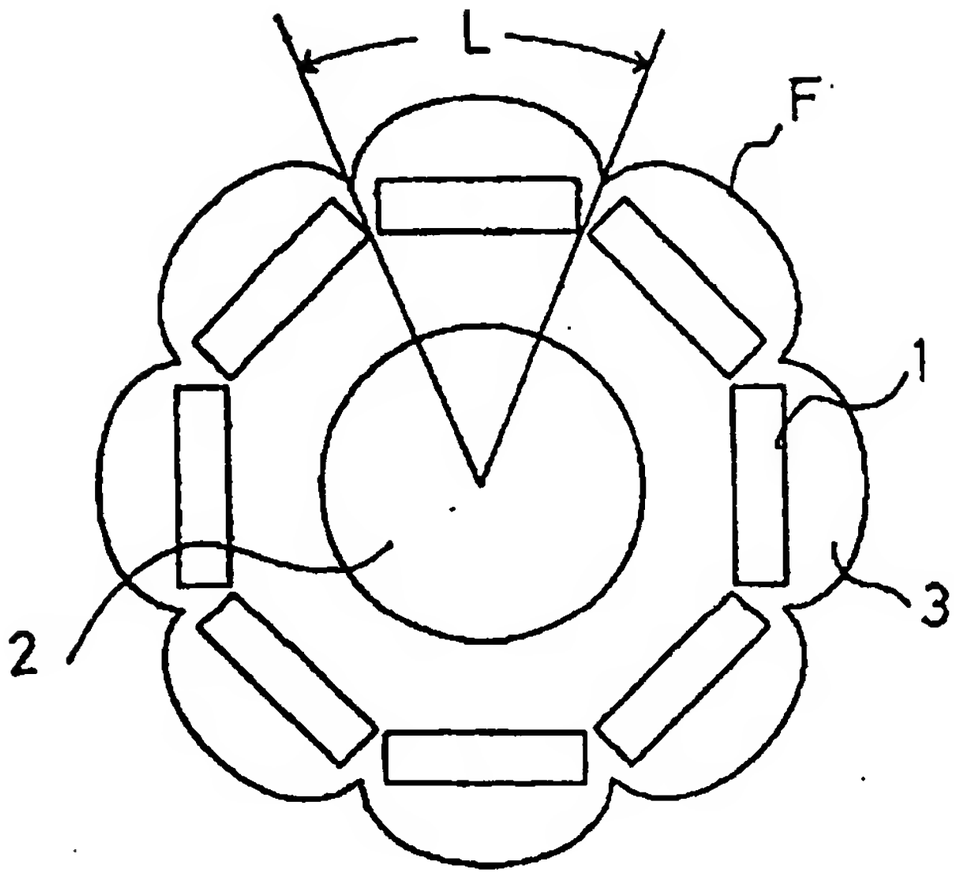


FIG. 2

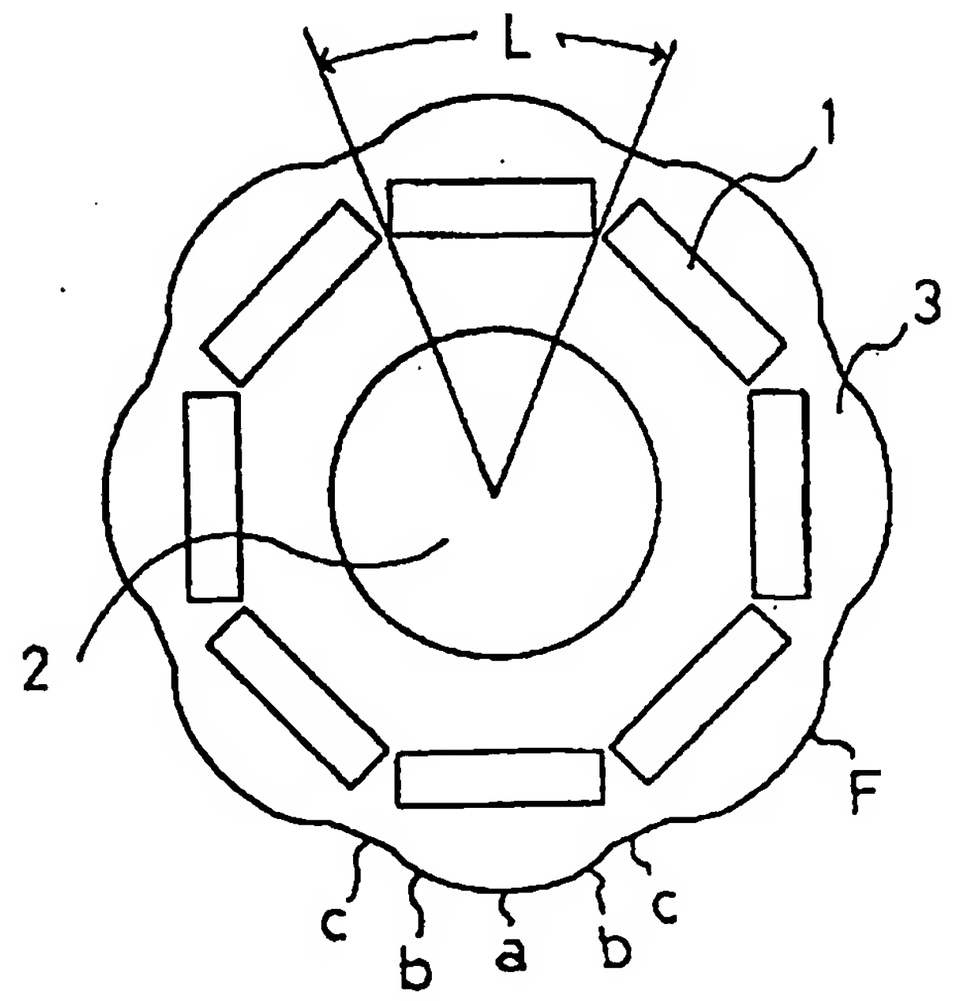


FIG. 3

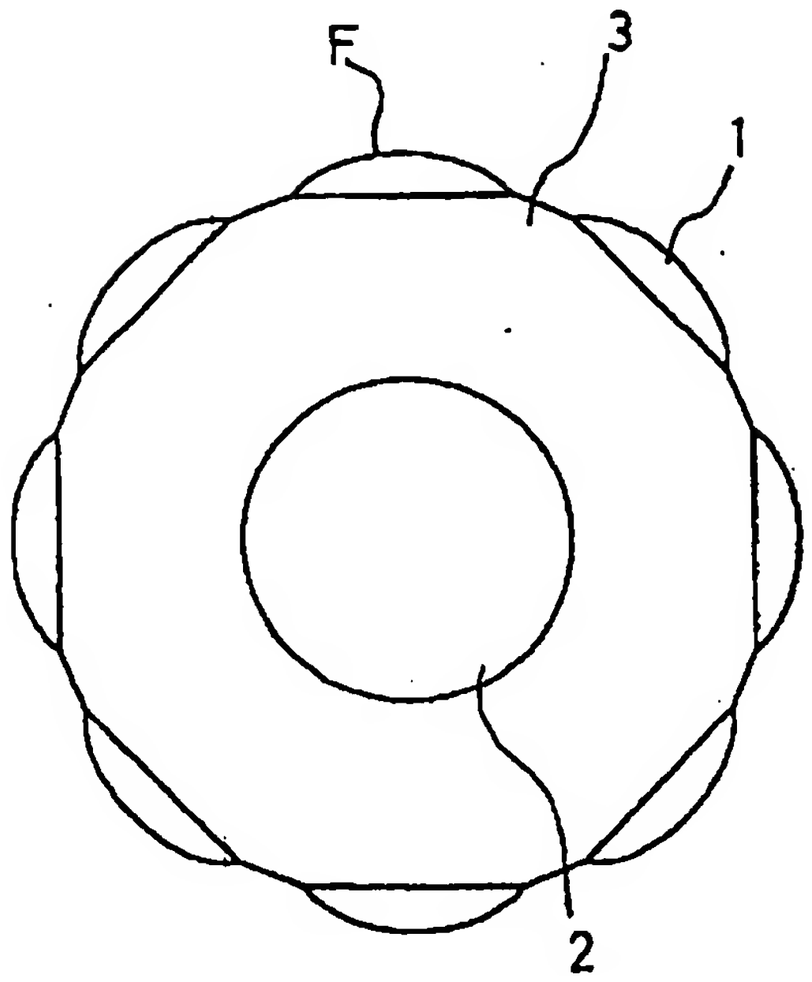


FIG. 4

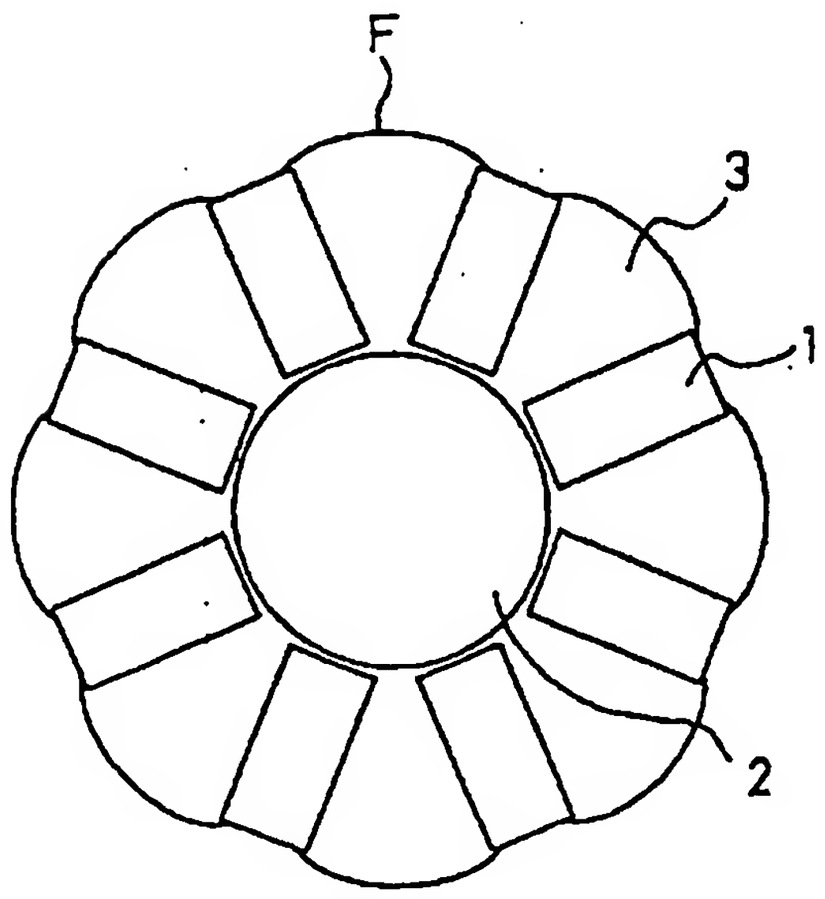
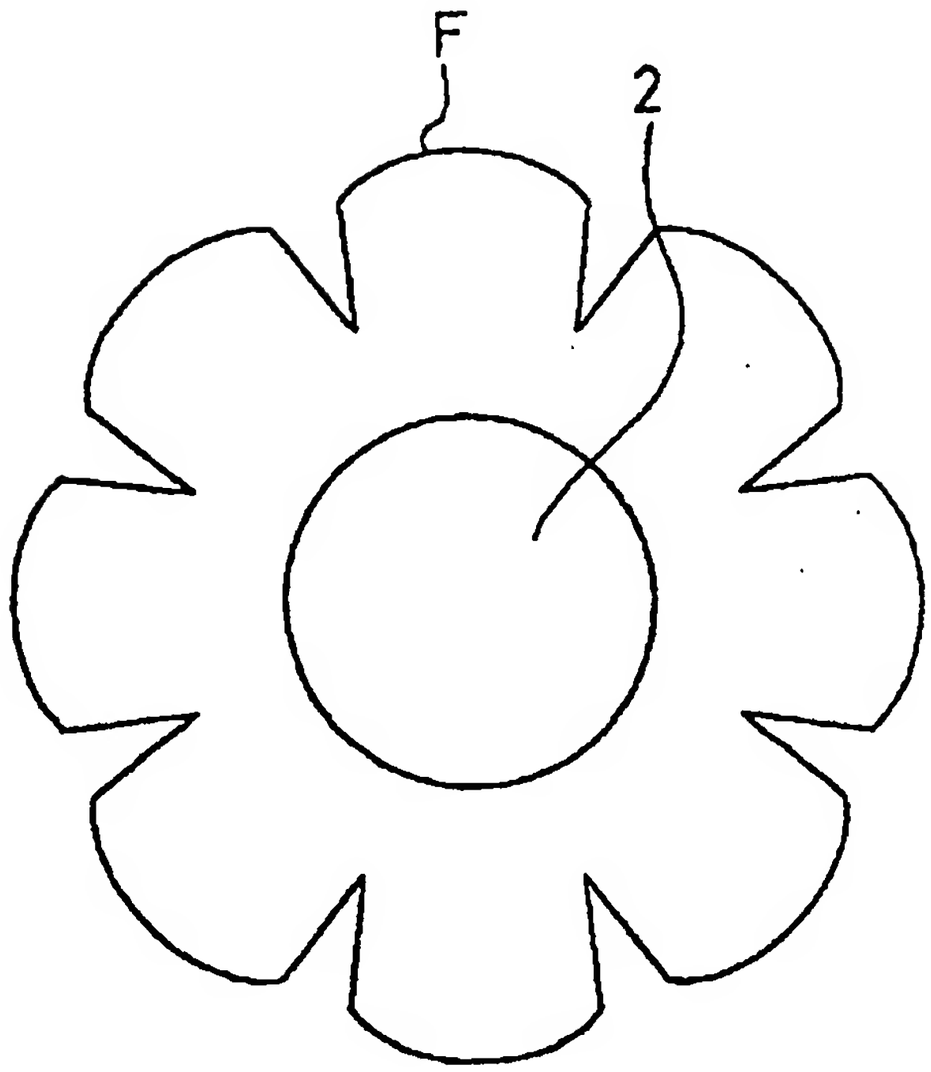


FIG. 5



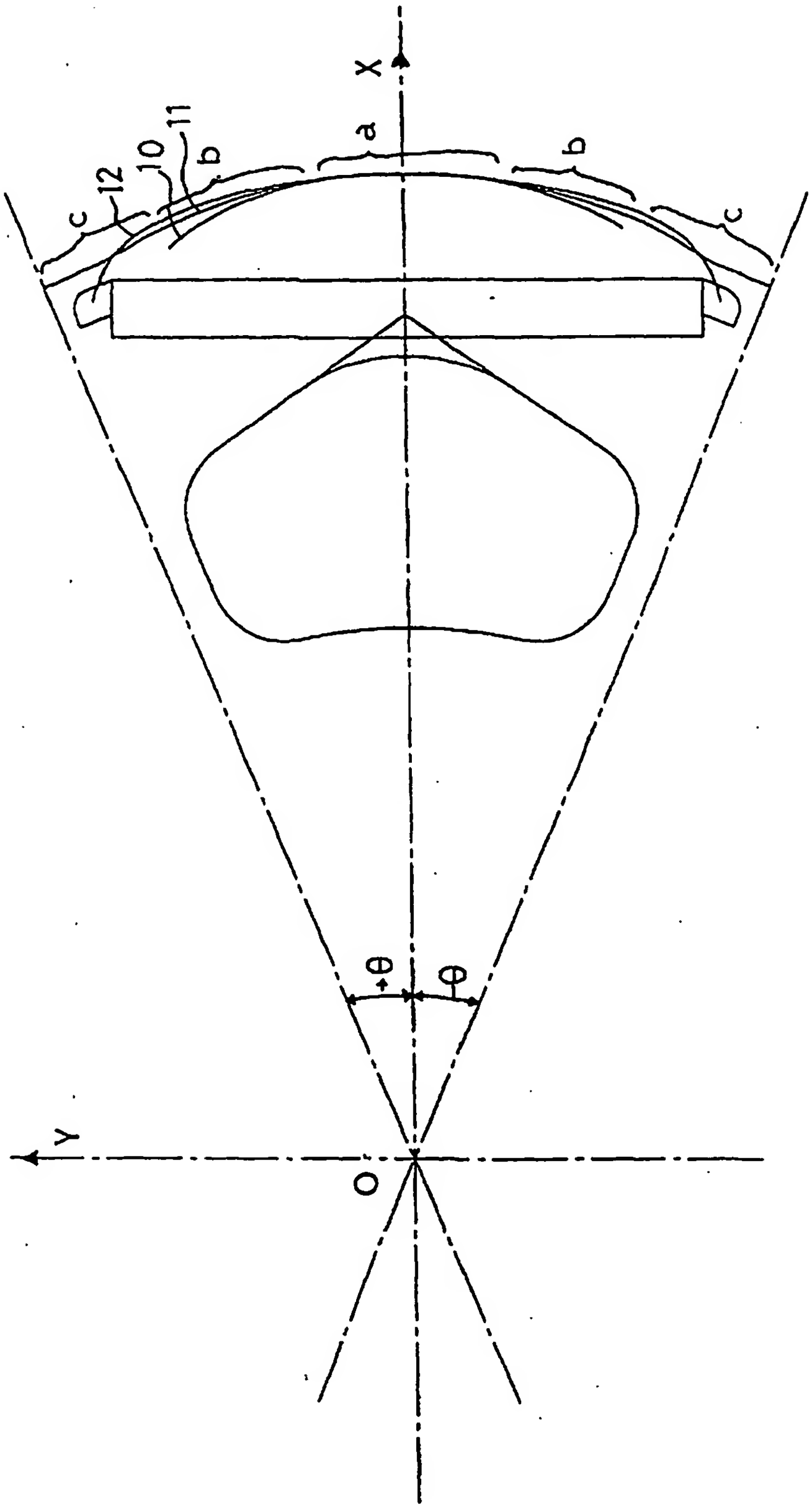


FIG. 6

FIG. 7

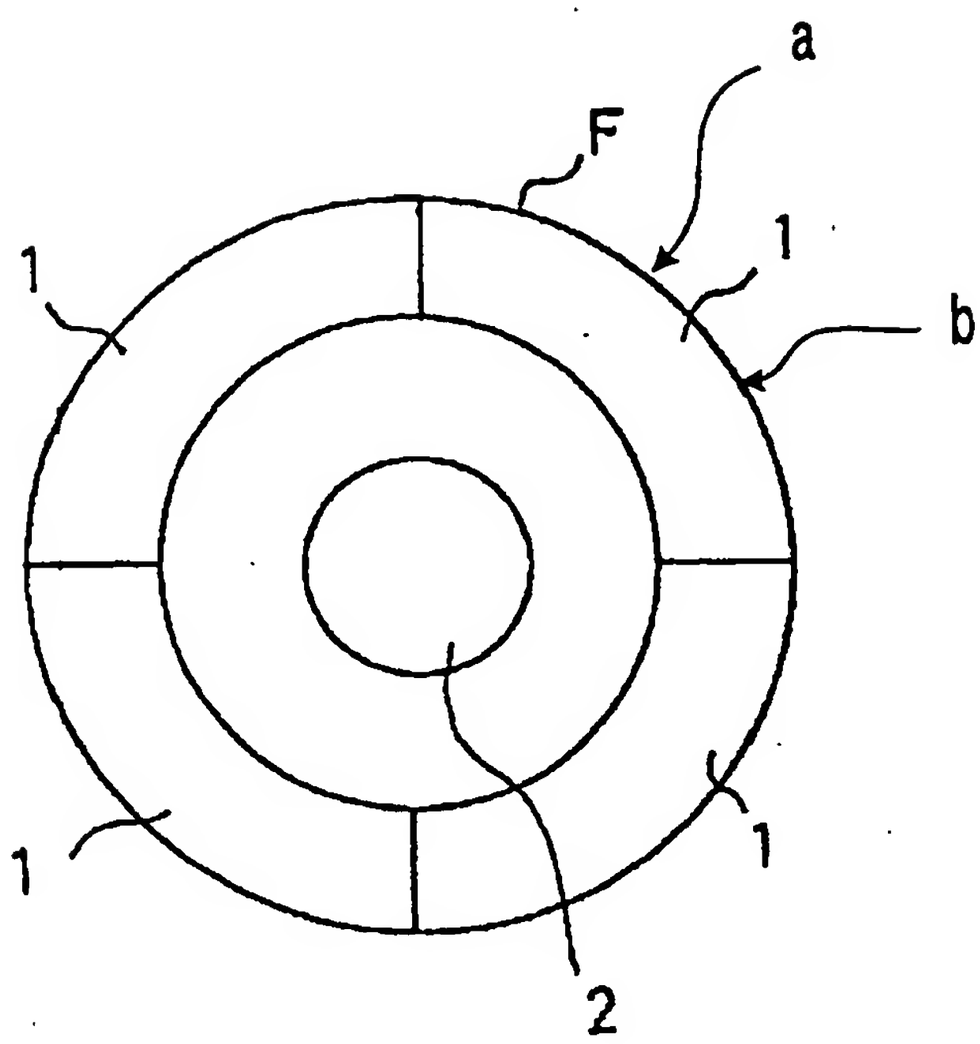
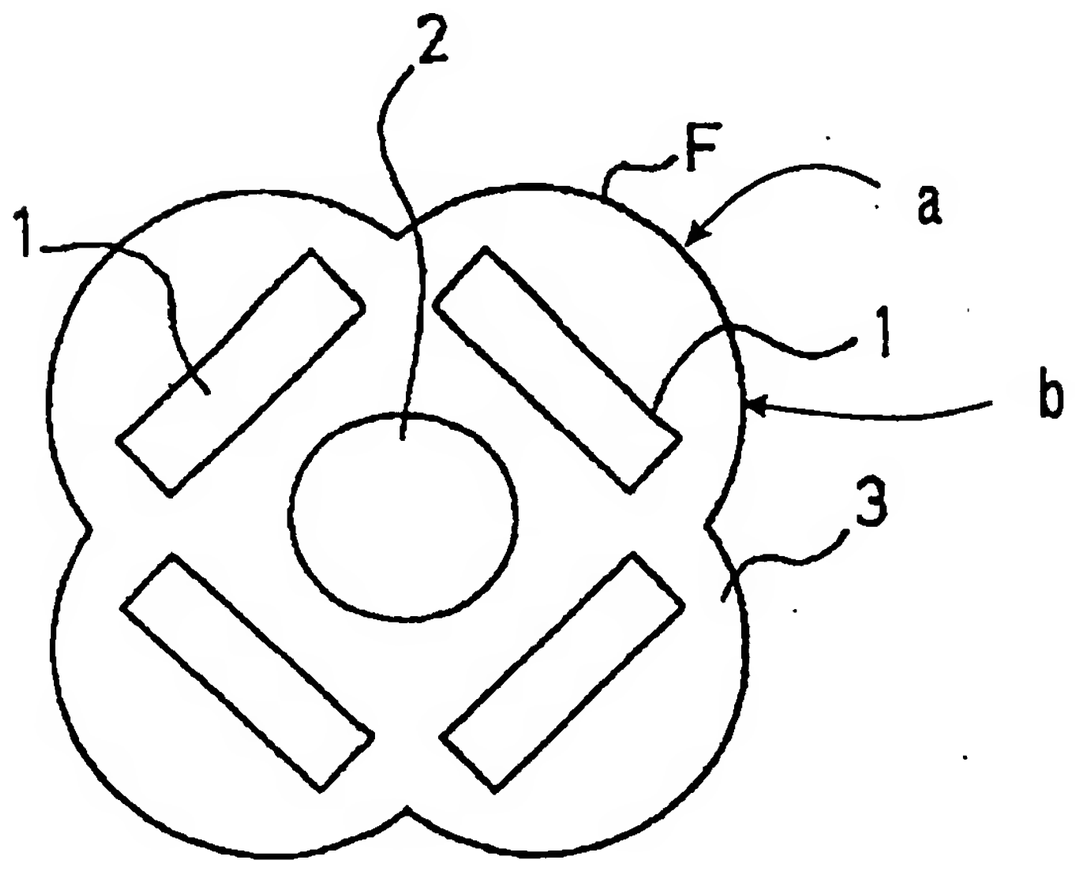



FIG. 8